TITLE
ASP Conference Series, Vol. **VOLUME***, **YEAR OF PUBLICATION**
NAMES OF EDITORS

Relativistic Jets from Collapsars: Gamma-Ray Bursts

Weiqun Zhang and S. E. Woosley

Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA

Abstract. Growing observational evidence supports the proposition that gamma-ray bursts (GRBs) are powered by relativistic jets from massive helium stars whose cores have collapsed to black holes and an accretion disk (collapsars). We model the propagation of relativistic jets through the stellar progenitor and its wind using a two-dimensional special relativistic hydrodynamics code based on the PPM formalism. The jet emerges from the star with a plug in front and a cocoon surrounding it. During its propagation outside the star, the jet gains high Lorentz factor as its internal energy is converted into kinetic energy while the cocoon expands both outwards and sideways. External shocks between the cocoon and the stellar wind can produce γ-ray and hard x-ray transients. The interaction of the jet beam and the plug will also affect both of them substantially, and may lead to short-hard GRBs. Internal shocks in the jet itself may make long-soft GRBs.

1. Introduction

Although there is no universally agreed upon central engine powering gamma-ray bursts (GRBs), growing evidence supports the association of least the long-soft GRBs (all those whose counterparts have been localized) with the death of massive stars. This evidence includes the association of GRBs with regions of massive star formation (Bloom, Kulkarni, & Djorgovski 2002) and "bumps" in the optical afterglows of several GRBs that have been related to the light curves of Type I supernovae (e.g., Bloom et al. 2002; Garnavich et al. 2002). In addition, GRB 980425 has been associated with SN 1998bw (e.g., Iwamoto et al. 1998; Woosley, Eastman, & Schmidt 1999). Frail et al. (2001), Panaitescu & Kumar (2001) have studied beaming angles and energies of a number of GRBs and have found that the central engines of GRBs release supernova-like energies. Given these discoveries, the currently favored models are all based upon the collapse of massive stars and their byproducts, one of which is a relativistic jet.

Among those models involving massive stars, the collapsar model (Woosley 1993; MacFadyen & Woosley 1999) has become a favorite. A "collapsar" is a rotating massive star whose iron core has collapsed and formed a black hole and an accretion disk. In this model, the central black hole and the disk use neutrinos or magnetic fields to extract part of the gravitational potential or rotational energy and form powerful relativistic jets along the polar axes. Jets from collapsars have been studied numerically in both Newtonian (MacFadyen & Woosley

1999; MacFadyen, Woosley, & Heger 2001) and relativistic simulations (Aloy et al. 2000; Zhang, Woosley, & MacFadyen 2002) and it has been shown that the collapsar model is able to explain many of the observed characteristics of GRBs. These previous studies have also raised issues which require further examination, especially with higher resolution. For instance, the emergence of the jet and its interaction with the material at the stellar surface and the stellar wind will definitely lead to some sort of "precursor" activity. The long term dynamics of the jet is critical in producing the observed gamma-rays and afterglows. We have recently carried out multi-dimensional calculations to address some of these issues.

2. Numerical Methods and Initial Conditions

A collapsar is formed when the core of a massive star collapses to a black hole and an accretion disk. The interaction of this disk with the hole, through processes that are still poorly understood, produces jets with a high energy to mass ratio. For our simulations, we are concerned primarily with the propagation of these relativistic jets, their interactions with the star and the stellar wind, and the observational implications, and not so much with how they are born. We model the propagation of relativistic jets inside and just outside collapsars using a multi-dimensional relativistic hydrodynamics code that has been used previously to study relativistic jets in the collapsar environment (Zhang et al. 2002). Briefly, our code employs an explicit Eulerian Godunov-type method developed by Aloy et al. (1999). Three-dimensional numerical simulations of relativistic jets in collapsars are still rather expensive, so the present study consists of a series of two-dimensional calculations with high resolution.

Our initial model is a $15\,M_\odot$ helium star calculated by Heger & Woosley (2002). The helium star has been evolved to iron core collapse. This presupernova model is then remapped into our two-dimensional cylindrical grid (r, z), which consists of 1500 zones in $0 \leq r \leq 6 \times 10^{11}$ cm and 2275 zones in $10^{10}\,\mathrm{cm} \leq z \leq 2 \times 10^{12}$ cm. In one of the models, we used a larger grid in r-direction, 2375 zones for $0 \leq r \leq 2 \times 10^{12}$ cm. In each case, the zoning is nonuniform with higher resolution in the inner region. The radius of the initial helium star is about 8×10^{10} cm and the surface of the star is very finely zoned. Outside the star, the background density, which comes from the stellar wind, is assumed to be $\sim R^{-2}$, and the density at $R = 10^{11}$ cm is set to $5 \times 10^{-11}\,\mathrm{g\,cm^{-3}}$, here R is the distance to the center of the star. This corresponds to a mass loss rate of $\sim 10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$ and a velocity of $\sim 1000\,\mathrm{km\,s^{-1}}$ at 10^{11} cm.

3. Results

We presume that a highly relativistic jet has already formed inside the inner boundary of our computational grid and study its evolution after it enters the grid. In particular, an axisymmetric jet is injected along the rotation axis through the inner boundary within a radius, r_0, here taken to be a free parameter. The initial jet is additionally defined by its total energy (excluding rest mass energy) flux per jet, $\dot{E}$, initial Lorentz factor, Γ_0, and the ratio of its kinetic energy to total energy, f_0. We have run a series of calculations: (A) $r_0 = 9\times10^8$ cm,

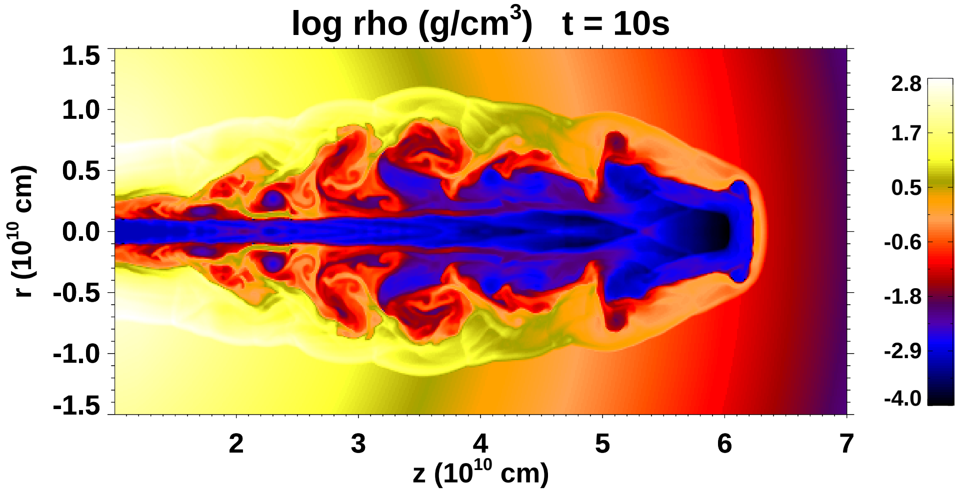

Figure 1. Density structure in the local rest frame for Model B at 10 s.

$\dot{E} = 3 \times 10^{50}\,\mathrm{erg\,s^{-1}}$, $\Gamma_0 = 5$, $f_0 = 0.025$; (B) $r_0 = 9 \times 10^8$ cm, $\dot{E} = 10^{50}\,\mathrm{erg\,s^{-1}}$, $\Gamma_0 = 10$, $f_0 = 0.05$; and (C) $r_0 = 9 \times 10^8$ cm, $\dot{E} = 5 \times 10^{49}\,\mathrm{erg\,s^{-1}}$, $\Gamma_0 = 5$, $f_0 = 0.025$. There presently exists no rigorous calculation of the jet formation process. However, a total energy of order $10^{51} - 10^{52}$ ergs is reasonable. The typical duration of a long GRB is ~ 20 seconds. In our calculations, the jet is left on for 20 seconds, and then gradually shut off (linearly with time). We know from observations that the GRB outflows are narrowly beamed. In our calculations, the radius of the jet is chosen to have a half-opening angle of $\sim 5°$ at 10^{10} cm. It is more difficult to estimate the Lorentz factor and the ratio of kinetic energy to total energy. As our previous studies showed, a jet that starts with a high Lorentz factor ~ 50 at 2000 km will be shocked and its Lorentz factor will become ~ 10 at 10^{10} cm (Zhang et al. 2002). For the parameters chosen, the jet starts with a Lorentz factor of 5 or 10 at 10^{10} cm, and would have a final Lorentz factor of ~ 180 if all internal energy is converted into kinetic energy.

3.1. Jets Inside Stars and the Emergence of Jets

In all models, the jet propagates along the rotational axis. After a short time, the jet consists of a supersonic jet beam; a cocoon made of shocked jet material and shocked medium; a terminal bow shock; a contact discontinuity; and backflows. A snapshot of Model B is shown in Figure 1. In agreement with our previous studies (Zhang et al. 2002), the jet in both models is narrowly collimated and its core, very thin. Interaction of the jet with the star and the cocoon imprints considerable time structure on the flow. As the jet passes through the star, it also explodes it.

Eventually, the jet breaks out the star. The average velocities of the head of the jet just before breakout are 9×10^9, 7×10^9, and $5 \times 10^9\,\mathrm{cm\,s^{-1}}$, for Models A, B, and C, respectively. As expected, the jet accelerates as it moves outwards because the density and pressure of the star decrease quickly, especially at the surface of the star. As the jet passes through the star, an over-pressurized

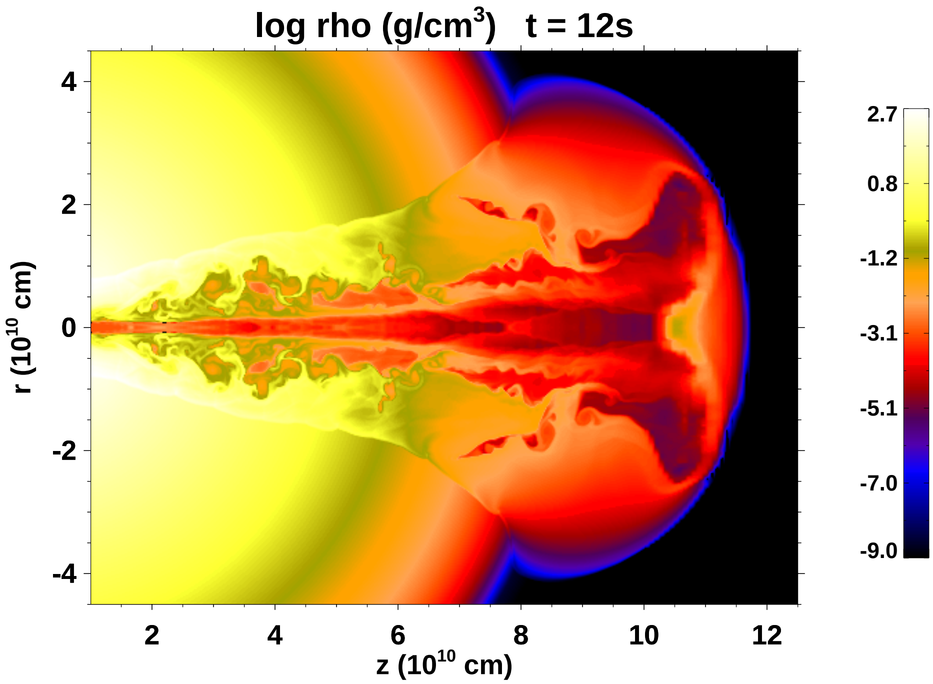

Figure 2. Density structure in the local rest frame for Model B at 12 s. The jet is breaking out the star. At the head of the jet, the cocoon is expanding sideways very quickly.

cocoon is formed. This cocoon escapes from the star along with the jet beam and accelerates as its internal energy is converted into kinetic energy by adiabatic expansion (Figure 2; see also Ramirez-Ruiz, Celotti, & Rees 2002). After the breakout into the low density stellar wind, the cocoon is no longer confined. The evolution of the jet and its cocoon in the stellar wind will be further discussed in § 3.2.

The velocity of the head of the jet in the star is subrelativistic, and the jet beam is highly relativistic. Shocked medium and shocked jet material piles up near the contact discontinuity and feeds the cocoon. This forms a "plug" at the head of the jet. After breakout, the initially subrelativistic plug will be moving at a Lorentz factor of $\sim 10-20$ since it is accelerated by the highly relativistic jet and the stellar wind cannot hinder its movement. The interaction of the "plug" and the jet and its implications for GRBs will be discussed in § 3.2 and § 4 (see also Waxman & Mészáros 2002).

3.2. Jets in the Stellar Wind

After it breaks out the star, both the jet and its cocoon are loaded with a lot of internal energy. Although its current Lorentz factor is only about 10, the final Lorentz factor of the jet can be ~ 200 if it can expand adiabatically to gain its terminal Lorentz factor. The Lorentz factor and density at the end of our simulation for Model A is shown in Figure 3. In all models, the average

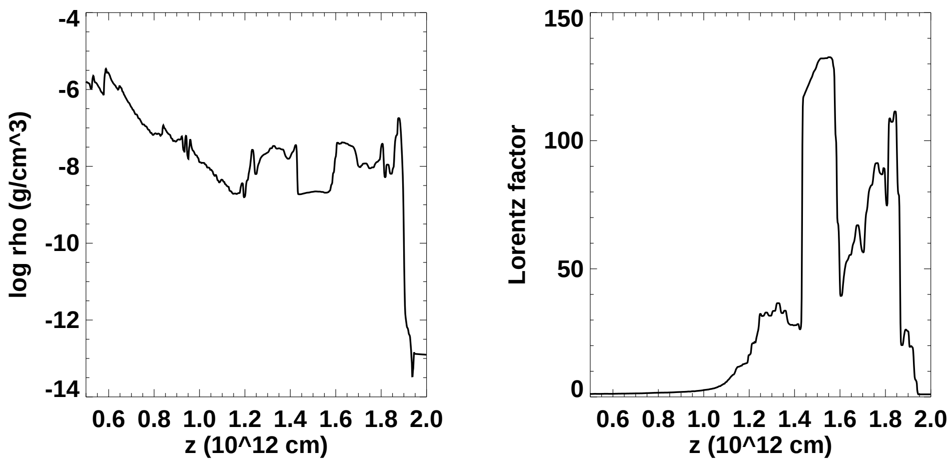

Figure 3. Density and Lorentz factor along the jet axis for Model A at 70 s. The Lorentz factor of the jet contains significant variabilities, which are very important for making γ-rays via internal shocks. Note the "plug" at the head of the jet. The plug has a moderate Lorentz factor.

Lorentz factor in the jets becomes more than 100 at the end of the simulations (t= 70 s), and there are still some internal energy remaining in the jets at that moment. When they are viewed on the axis, the jets have an isotropic equivalent total energy of 3×10^{54}, 4×10^{54}, and 5×10^{53} erg, for Models A, B, and C, respectively[1]. This energy should be enough to power a normal GRB even if the efficiency for making γ-rays is very small.

After the jet breaks out the star, its cocoon expands both outwards and sideways (Figure 2). An interesting effect of the cocoon is that it prevents the jet beam from expanding sideways. Without the cocoon, a bare "hot" jet with a Lorentz of about 10 will inevitably expand sideways (Zhang et al. 2002). The cocoon emerges out the star with an energy close to the total energy injected at the base of the jet before the jet emerges from the star (Ramirez-Ruiz et al. 2002). The conversion of its internal energy into kinetic will give the cocoon a Lorentz factor of $\sim 5 - 10$ and the cocoon can reach up to 30°. For instance, the isotropic equivalent energy of relativistic material at 30° is about 10^{50} erg for Model C. In Models A and B it is an order of magnitude greater.

The jet breaks out the star with a plug in front of it. The plug is made of the shocked stellar and jet material. After breakout, the plug has comparable density to that of the jet, and a Lorentz factor of about 10-20 (see e.g., Figure 3). In Model A, the total rest mass in the plug at 70 s, is about 10^{28} g, which is $\sim 1/5$ of that of the jet. They are 6×10^{27} and 2×10^{27} g, about half of that of the jet, for Models B and C, respectively. These massive plugs will surely alter

[1]Note that the jets are beamed into $\sim 5°$. The isotropic equivalent energy is derived by assuming an isotropic fireball instead of a jet

the structure of the GRB jets. The interaction of the jet and the plug will accelerate the plug. Meanwhile, the jet will be slowed down. Part of its kinetic energy will be converted into its internal energy. This interaction may have important implications for observations.

4. Discussion

Our special relativistic calculations show that a jet originating near the center of a collapsing massive will emerge while still carrying almost all the energy injected at the center. After it breaks out of the star, the jet will move forward almost freely, no more cocoon will be generated. The standard fireball model requires not only high Lorentz factor, but also the Lorentz factor to vary rapidly. Our simulations show promise in satisfying these constraints. However, due to the low resolution ($\Delta z = 1.6 \times 10^9$ cm) outside the star, it is hard to resolve those small scale variabilities and the numerical viscosity gradually smooths the time structure in the jet.

We have found that the cocoon can expand sideways up to $\sim 30°$ after it emerges from the star. The deceleration of the cocoon by external shocks will produce γ-rays and x-rays (see also Ramirez-Ruiz et al. 2002). The "anomalous" GRB 980425 might be a cocoon viewed from a large angle. It might also contribute to the afterglows and precursors of a normal GRB and may be the origin of recently discovered hard x-ray flashes (Heise et al. 2001; Kippen et al 2002). These flashes have many properties of GRBs (energy, isotropy, approximate duration, distribution with redshift), but have a much softer spectrum (and so far no optical afterglow). The association of this kind of softer transient with gamma-ray bursts seen off-axis has been predicted by our group for many years (Woosley et al 1999; Woosley & MacFadyen 1999; Woosley 2000, 2001).

Behind the bow shock, there is a plug in front of the jet beam. After breakout, the main jet beam continues to push and accelerate this plug. Meanwhile, the jet beam is slowed down as its energy is transfered to the plug and part of its kinetic energy is converted into its internal energy. The basic picture of a fast moving jet beam pushing a "slowly" moving plug is that there is a reverse shock, which moves backward and slows down the jet beam, a contact discontinuity, and a forward shock. Since the plug has a limited length, the forward shock will reflect at the end of the plug. This further complicates the dynamics (e.g., Waxman & Mészáros 2002).

At the end of our simulation, the jet and the plug are moving relativistically and the stellar wind has not been able to decelerate the jet, so we can make some analytic estimates treating the jet and the plug as a spherical symmetric fireball.

Where will the jet and the plug become optically thin? In our case, the opacity in the jet and the plug is dominated by Thomson scattering. The optical depth is $\tau = \kappa \Sigma = \kappa \rho \Delta r = \kappa (M/4\pi r^2) = \tau_0 (r_0/r)^2$, here, $\kappa \sim 0.2\,\mathrm{cm^2\,g^{-1}}$, and τ_0 is the initial optical depth at r_0. From our results at $t = 70$ s, the plug will become optically thin at $r_{\rm th,p} = 2.0 \times 10^{14}$, 2.6×10^{14}, and 1.7×10^{14} cm, for Models A, B, and C, respectively. And the jet will become optically thin at $r_{\rm th,j} = 5.8 \times 10^{14}$, 7.6×10^{14}, and 2.9×10^{14} cm, for Models A, B, and C, respectively. When it becomes optically thin, the interaction of the plug with the jet, will produce hard emission. In fact, it is possible that this emission could be a short-hard GRB (as defined in Fishman & Meegan 1995).

Where will the jet catch up the plug and be decelerated by the plug? This is a very critical question. During the catch-up period, some of the kinetic energy of the jet is converted into internal energy. If the deceleration happens in the optically thick regime, the increased internal energy can still be converted back into kinetic energy. If, however, it happens in the optically thin regime, the increased internal energy will become radiation energy via this special kind of "internal shock" and escape from the jet. There may not be enough kinetic energy left and high enough Lorentz factor to make γ-rays via "normal" internal shocks. In this case, the short hard precursors from the plug may dominate at X-ray and γ-ray wavelengths, and a short hard GRB is likely to be seen. Numerical simulations on the catch-up process are currently underway. We analytically estimate the radius, $r_{\rm cat}$, at which the catch-up process will happen. For simplicity we assume that the jet moves at a Lorentz factor of 100, the plug moves at a Lorentz factor of 20, and the length of the jet is about 5×10^{11} cm, then we get $r_{\rm cat} \sim 5 \times 10^{14}$ cm. This radius is comparable to the radius where the jet becomes optically thin. Our simulations show a tendency for the energy in the plug relative to that in the jet behind the plug to be larger when the total energy is less (see § 3.2). This suggests that less energetic jets may be more likely to make short-hard GRBs. The near coincidence of the masses of the plug and jet and of the radii where the two share their energy with the gamma-ray photosphere suggests that there may be cases where the most prominent display comes from the plug and others where it still comes from internal shocks in the jet (or at the jet-plug interface).

Where will the jet be decelerated by the stellar wind? The deceleration by the stellar wind happens when the jet sweeps up $1/\Gamma$ of its rest mass, here Γ is the Lorentz factor of the jet. Assuming a stellar wind that has a mass loss rate of $\sim 10^{-5}\, M_\odot\, {\rm yr}^{-1}$ and a velocity of $\sim 1000\, {\rm km\, s}^{-1}$ at 10^{11} cm, the deceleration radius, $r_{\rm dec}$, is 3×10^{16} cm for Model A. And they are 4×10^{16} and 8×10^{15} cm, for Models B and C, respectively. The deceleration by external shocks with the stellar wind always happens after the above events. This justifies our one-dimensional analytic calculations because the effects of the sideways expansion are negligible when the jets are highly relativistic.

In our numerical simulations, We have followed the propagation of jets to $r = 2 \times 10^{12}$ cm. However, many interesting events which are directly related to observations happen at large radius. So the long time evolution of the jets in the stellar wind is very critical. It will help us make many testable predictions. Numerical calculations which follow the long time evolution of the jets are under way. Hopefully, they will further strengthen our knowledge on relativistic outflows of GRBs.

It is also very important to repeat our simulations in three-dimensional Cartesian coordinates.

Acknowledgments. This research has been supported by NASA (NAG5-8128, NAG5-12036, and MIT-292701) and the DOE Program for Scientific Discovery through Advanced Computing (SciDAC; DE-FC02-01ER41176). We are indebted to Alex Heger for providing the precollapse model used in this calculation and to illuminating conversations with Chris Matzner, Martin Rees, and Enrico Ramirez-Ruiz.

References

Aloy, M. A., Ibáñez, J. Mª., Martí, J. Mª., & Müller, E. 1999, ApJS, 122, 151

Aloy, M. A., Müller, E., Ibáñez, J. Mª., Martí, J. Mª., & MacFadyen, A. I. 2000, ApJ, 531, L119

Bloom, J. S., Kulkarni, S. R., Djorgovski, S. G., Eichelberger, A. C., Cote, P., Blakeslee, J. P., Odewahn, S. C., Harrison, F. A., et al. 1999, Nature, 401, 453

Bloom, J. S., Kulkarni, S. R., Price, P. A., Reichart, D., Galama, T. J., Schmidt, B. P., Frail, D. A., Berger, E., et al. 2002, ApJ, 572, L45

Bloom, J. S., Kulkarni, S. R., & Djorgovski, G. 2002, AJ, 123, 1111

Fishman, G. J., & Meegan, C. A. 1995, ARA&A, 33, 415.

Frail, D., et al. 2001, ApJ, 562, L55

Galama, T. J., Tanvir, N., Vreeswijk, P. M., Wijers, R. A. M. J., Groot, P. J., Rol, E., van Paradijs, J., Kouveliotou, C. et al. 2000, ApJ, 536, 185

Garnavich, P. M., et al. 2002, ApJ, submitted, astro-ph/0204234

Heger, A., & Woosley, S. E. 2002, to appear in Proc. Woods Hole GRB meeting, ed. R. Vanderspek, astro-ph/0206005

Heise, J., in't Zand, J., Kippen, R. M., Woods, P. M. 2001, GRBs in the Afterglow Era, eds. Costa, Frontera, & Hjorh, ESO Astrophysics Symposia, (Springer), 16, astro-ph/0111246.

Iwamoto, K., et al. 1998, Nature, 395, 672

Kippen, R. M., Woods, P. M, Heise, J., in 't Zand, J. J. M., Briggs, M. S., & Preece, R. D. 2002, in proceedings of the Woods Hole GRB Workshop, ed. R. Van der Speck, in press, astro-ph/0203114.

MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262

MacFadyen, A. I., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 410

Panaitescu, A., & Kumar, P. 2001, ApJ, 560, L49

Ramirez-Ruiz, E., Celotti, A., & Rees, M. J. 2002, MNRAS, in press astro-ph/0205108

Waxman, E., & Mészáros, P. 2002, ApJ, submitted, astro-ph/0206392

Woosley, S. E. 1993, ApJ, 405, L273

Woosley, S. E., Eastman, R. G., & Schmidt, B. 1999, ApJ, 516, 788

Woosley, S. E. & MacFadyen, A. I. 1999, A&AS, 138, 499

Woosley, S. E. 2000, GRBs, 5th Huntsville Symposium, eds. Kippen, Mallozzi, & Fishman, AIP, Vol 526, 555

Woosley, S. E. 2001, GRBs in the Afterglow Era, eds. Costa, Frontera, & Hjorh, ESO Astrophysics Symposia, (Springer), 555

Zhang, W., Woosley, S. E., & MacFadyen, A. I. 2002, ApJ, in press, astro-ph/0207436